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LCA FOR AGRICULTURE • CASE STUDY

# Life cycle assessment of corn grain and corn stover in the United States

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**Abstract**

*Background, aim, and scope* The goal of this study is to estimate the county-level environmental performance for continuous corn cultivation of corn grain and corn stover grown under the current tillage practices for various corn-growing locations in the US Corn Belt. The environmental performance of corn grain varies with its farming location because of climate, soil properties, cropping management, etc. Corn stover, all of the above ground parts of the corn plant except the grain, would be used as a feedstock for cellulosic ethanol.

*Materials and methods* Two cropping systems are under investigation: corn produced for grain only without collecting corn stover (referred to as CRN) and corn produced for grain and stover harvest (referred to as CSR). The functional unit in this study is defined as dry biomass, and the reference flow is 1 kg of dry biomass. The system boundary includes processes from cradle to farm gate. The default allocation procedure between corn grain and stover in the CSR system is the system expansion approach. County-level soil organic carbon dynamics, nitrate losses due to leaching, and nitrogen oxide and nitrous oxide emissions are simulated by the DAYCENT model. Life cycle environmental impact categories considered in this study are total fossil energy use, climate change (referred to as greenhouse gas emissions), acidification, and eutrophication. Sensitivities on farming practices and allocation are included.

*Results* Simulations from the DAYCENT model predict that removing corn stover from soil could decrease nitrogen-related emissions from soil (i.e., $N_2O$, $NO_x$, and $NO_3^-$ leaching). DAYCENT also predicts a reduction in the annual accumulation rates of soil organic carbon (SOC) with corn stover removal. Corn stover has a better environmental performance than corn grain according to all life cycle environmental impacts considered. This is due to lower consumption of agrochemicals and fuel used in the field operations and lower nitrogen-related emissions from the soil.

*Discussion* The primary source of total fossil energy associated with biomass production is nitrogen fertilizer, accounting for over 30% of the total fossil energy. Nitrogen-related emissions from soil (i.e., $N_2O$, $NO_x$, and $NO_3^-$ leaching) are the primary contributors to all other life cycle environmental impacts considered in this study.

*Conclusions* The environmental performance of corn grain and corn stover varies with the farming location due to crop management, soil properties, and climate conditions. Several general trends were identified from this study. Corn stover has a lower impact than corn grain in terms of total fossil energy, greenhouse gas emissions, acidification, and eutrophication. Harvesting corn stover reduces nitrogen-related emissions from the soil (i.e., $N_2O$, $NO_x$, $NO_3^-$). The accumulation rate of soil organic carbon is reduced when corn stover is removed, and in some cases, the soil organic carbon level decreases. Harvesting only the cob portion of the stover would reduce the negative impact of stover removal on soil organic carbon sequestration rate while still bringing the benefit of lower nitrogen-related emissions from the soil. No-tillage practices offer higher accumulation

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rates of soil organic carbon, lower fuel consumption, and lower nitrogen emissions from the soil than the current or conventional tillage practices. Planting winter cover crops could be a way to reduce nitrogen losses from soil and to increase soil organic carbon levels.

*Recommendations and perspectives* County-level modeling is more accurate in estimating the local environmental burdens associated with biomass production than national- or regional-level modeling. When possible, site-specific experimental information on soil carbon and nitrogen dynamics should be obtained to reflect the system more accurately. The allocation approach between corn grain and stover significantly affects the environmental performance of each. The preferred allocation method is the system expansion approach where incremental fuel usage, additional nutrients in the subsequent growing season, and changes in soil carbon and nitrogen dynamics due to removing corn stover are assigned to only the collected corn stover.

**Keywords** Biorefinery · Cob · Corn · Life cycle assessment · Soil organic carbon · Stover · Tillage · Winter cover crop

## 1 Background, aim, and scope

There are increasing concerns about the effects of agricultural practices on soil quality, soil erosion, and water quality. For example, nitrogen fertilizer runoff from the agriculturally intensive Midwest of the United States is widely believed to be a significant contributor to the anoxic conditions that prevail from time to time in the Gulf of Mexico (Goolsby et al. 2001). At the same time, more and more agricultural raw materials are being used to produce fuels, chemicals, and other industrial products, collectively described as bio-based products. Several studies show that bio-based products can save crude oil and reduce greenhouse gas emissions (Kim and Dale 2002; Kim and Dale 2005a, b; Shapouri et al. 2000; Sheehan et al. 2002; Vink et al. 2003; Wang 2000; Wu et al. 2006a). Since agricultural processes account for a large fraction of the total energy consumption in producing bio-based products (27–44% for the products studied in Kim and Dale 2004), sustainable agricultural practices are a key factor to improve the environmental performance of bio-based products.

Currently, bio-based products are derived mostly from starch biomass. For example, most ethanol produced in the United States is derived from corn grain (RFA 2007). Polylactides and polyhydroxyalkanoates are also made from corn grain (Kim and Dale 2005b; Vink et al. 2003). The availability of corn grain for producing bio-based products is limited. Another potential feedstock for bio-based products is cellulosic biomass such as agricultural residues (e.g., corn stover, crop straws, and sugarcane bagasse), herbaceous crops (e.g., alfalfa, switchgrass), short rotation woody crops, forestry residues, wastepaper, and other wastes (Office of Energy Efficiency and Renewable Energy 2006). Corn stover refers to all of the above ground parts of the corn plant except grain. Approximately equal masses of stover and grain are produced. Most corn stover in the United States is left in the fields. About 5% of the total corn stover is removed from the fields for animal feed and bedding (Glassner et al. 1999). Removing corn stover from the fields could possibly increase soil erosion and reduce soil organic carbon levels (Mann et al. 2002). Previous studies (Graham et al. 2007; Nelson 2002) predict the availability of corn stover in the United States as feedstock for bio-based products based on a tolerable level of soil erosion.

A number of publicly available corn-farming studies have been conducted to provide input to a national policy debate on the energy efficiency of fuel ethanol from corn grain (Shapouri et al. 2002; Wang 2000; Wu et al. 2006a). In that context, it may be appropriate to work with US average data on corn farming and focus on selected impacts (e.g., fossil energy consumption). However, to evaluate other impacts on the farming ecosystem, like soil organic carbon level, climate change, and eutrophication, location-specific factors have to be considered. To estimate local soil carbon and nitrogen dynamics in biomass cultivation, this study uses the DAYCENT model, which is the daily time step version of the CENTURY model, a multicompartmental ecosystem model (Del Grosso et al. 2000, 2001; Natural Resource Ecology Laboratory 2005).

This study is a part of the Integrated Corn-Based Biorefinery (ICBR) project sponsored by the US Department of Energy and DuPont. The ICBR concept is to convert corn stover into fermentable sugars for the production of fuel ethanol. The goal of this study in the ICBR project is to estimate the county-level life cycle analysis data on corn grain and corn stover in various corn-growing locations. The United States produces annually 261 Tg ($261 \times 10^{12}$ g) of corn grain, and over 80% of the total corn in the United States is produced in Corn Belt States—Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Nebraska, North and South Dakota, Ohio, and Wisconsin (NASS 2007). This study selects corn-growing locations from only Corn Belt States to estimate the environmental burdens associated with corn grain and corn stover productions.

## 2 Goal and scope

### 2.1 Goal

The goal of this study is to estimate the county-level environmental performance for continuous corn cultivation

of corn grain and corn stover in various corn-growing locations in Corn Belt States. Two cropping systems are under investigation: corn produced for grain only without collecting corn stover (referred to as CRN) and corn produced for corn grain and corn stover harvest (referred to as CSR). The products in the CSR system are corn grain and corn stover, while the product in the CRN system is only corn grain.

## 2.2 Functional unit

The function of biomass (i.e., corn grain and corn stover) for the purposes of this study is to provide components (starch, cellulose, hemicellulose, lignin, protein, etc.) to be used as raw materials for bio-based products in the ICBR system. This study focuses on only the agricultural process (namely, biomass production), so the functional unit is defined as dry biomass, and the reference flow is 1 kg of dry biomass. Life cycle assessment (LCA) results are reported for 1 kg of dry grain and 1 kg of dry stover.

## 2.3 System boundaries

The system boundaries of this LCA are cradle to farm gate. This includes the burden of all input processes to the corn grain and stover farming system, back to raw materials extracted from the ground through exiting the farm. Farm equipment production systems are not included in the system boundary because of their small contribution to the overall impact (Graboski 2002). Infrastructure (e.g., road, rail, etc.) is also excluded in the analysis due to lack of reliable data. Transportation of biomass to the biorefinery is not included in this system, but should be considered in a biorefinery LCA.

## 2.4 Geographic scope

Since crop management varies with corn-farming location, this study selects specific corn-growing locations. The selected corn-farming locations represent a broad range of typical Corn Belt soil and climate conditions. Agricultural data (i.e., soil texture and climate) are available for each location, which is required in order to simulate soil carbon and nitrogen dynamics. Local presence of a dry milling plant, a coal-fired power plant, and railroad infrastructure were also considered as criteria for location selection. The presence of a coal-fired power plant could facilitate the utilization of lignin-rich residues from the ICBR process. Eight counties in seven different states in the Unites States are studied based on the above criteria and are illustrated in Fig. 1: Hardin County (IA), Fulton County (IL), Tuscola County (MI), Morrison County (MN), Freeborn County (MN), Macon County (MO), Hamilton County (NE), and Codington County (SD).

## 2.5 Input data

County-level corn yield data are available at the National Agricultural Statistics Service (NASS 2007). State-level agronomic inputs (fertilizers and agrochemicals) and fuel consumption are also available at the NASS (2007) and at the Economic Research Service (ERS 2005), respectively. The state-level values are used in the agronomic inputs and fuel consumption instead of county-level values due to lack of county-level information. This study uses 4-year average values over year 2000 through year 2003 for corn yield and agronomic inputs and values of year 2001 for fuel consumption. Table 1 summarizes corn yield and agronomic inputs in each county. The lime application rates are obtained from Shapouri et al. (2002). No coproduct allocation is considered for ammonia production, an input for N fertilizer. Although other allocation options could be considered, it is conservative to assume that all $CO_2$ generated from ammonia production are emitted to the environment (Kim and Dale 2004).

Table 2 summarizes the current tillage practices and the climate and precipitation data used for each county. In no-tillage farming, greater than 30% of the residue is left on the soil surface and the soil is left undisturbed from harvest to planting except for strips up to one third of the row width. In conventional tillage farming, less than 15% of the residue is left on the soil surface and full width tillage, which disturbs the entire soil surface, is performed prior to and/or during planting (Conversation Technology Information Center 2003). The environmental burdens associated with biomass grown under no-tillage and conventional tillage practices are also estimated separately in the scenario analyses section. Rainfall is the average monthly centimeters of precipitation in the growing season and all data in Table 2 are county-level. Only two counties among eight counties use irrigation: Hamilton County in Nebraska and Codington County in South Dakota. About 97% of the total corn produced in Hamilton County is grown under irrigation, while only 4% of the total in Codington County is grown under irrigation (Graboski 2002).

Stover removal rates used in this study are shown in Table 2. They were set so as to meet erosion tolerances with a maximum of 50% stover removal. Nelson (2002) estimates these statewide corn stover removal rates, which are based on no-tillage and mulch tillage practices but do not consider conventional tillage. Due to variations in yield, tillage practice, soil type, climate, precipitation, and field characteristics, these stover removal rates may not be appropriate for all farming locations within each county. However, it is reasonable to assume that, in many

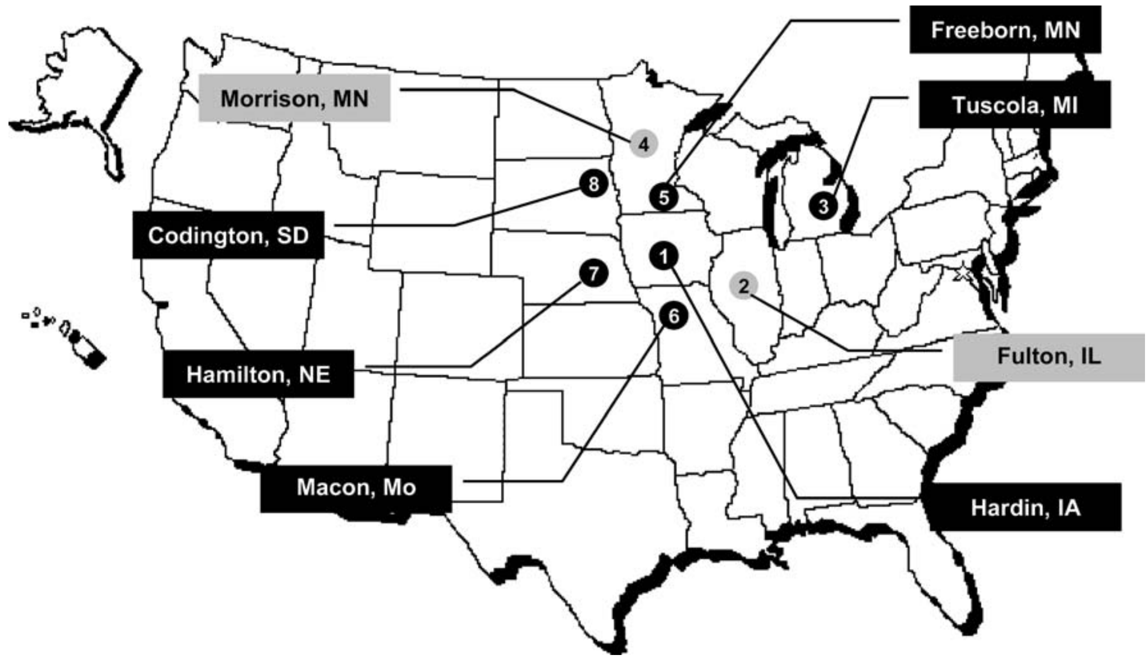


**Fig. 1** Farming locations selected for analysis [*black circle* county has a coal-fired power plant, *gray circle* county does not have a coal-fired power plant but adjacent county does]

instances, the stover removal rates used in this study would be acceptable and keep erosion within tolerable limits.

Corn stover is assumed to be harvested in a second pass (Sheehan et al. 2002). It is assumed that no ammonia volatilization loss from nitrogen fertilizer occurs because soil pH in all the counties is below 7 and N fertilizers are incorporated or injected (Meisinger and Randall 1991). A sensitivity analysis investigates the effects of ammonia loss. Phosphorus losses would occur from two sources: (1) phosphorus fertilizer and (2) crop residues. The loss rate of phosphorus from phosphorus fertilizer assumed in this study is from Zhao et al. (2001), and the leaching rate of phosphorus from corn stover is from Schreiber's study (1999). The life cycle inventory information on the upstream processes were obtained from literature (EFMA 2000a, b, c; Gerhartz 1996; Jimenez-Gonzalez et al. 2000; Kim and Dale 2005c; Kim and Overcash 2000; Office of Industrial Technologies 2000; Pagani and Zardi 1994) and commercial LCA databases (Ecobilan 2007).

## 3 Materials and methods

The DAYCENT model simulates soil organic carbon dynamics, nitrate losses due to leaching, and nitrogen oxide and nitrous oxide emissions. Required input parameters for the DAYCENT model are county-level climate information, which is available at the National Climatic Data Center (2007), soil properties (NSSC Soil Survey Laboratory 2005), and crop management (Conservation Technology Information Center 2003). Since other site-specific soil properties (e.g., organic carbon, moisture, mineral contents, etc.) are not available, the model is run for 1,860 years with default values given by the model to generate the initial site-specific soil properties and to equilibrate the modeling run. In the initialization (or "spin-up" process), native grasses are assumed to be dominant for 1,860 years to reach a steady state condition. Then, the crop history of western Iowa (from 1861 to 1994) given by Kristen et al. (2000) is followed because no information is available on the crop history of all counties considered in this study. After the crop history, a corn–soybean rotation for 10 years is run to reflect the current crop practice. Continuous corn culture under no-tillage for 10 years is then simulated to align the model for changes to continuous corn culture. After completing the spin-up process and the crop history, corn cultivation is simulated for 100 years with the climate data from year 1961 to year 2003. The DAYCENT model predicts the accumulation or depletion rate of soil organic carbon, $N_2O$ and $NO_x$ emissions from soil, and $NO_3^-$ leaching. Due to a lack of specific information, the application rate of nitrogen fertilizer in each county is assumed to remain the same throughout the 100 years. Effects due to the spin-up process and the crop history are investigated in sensitivity analyses. Carbon sequestration by soil due to increasing soil organic carbon level and nitrogen-related emission rates (i.e., $N_2O$, $NO_x$, $NO_3^-$) are

**Table 1** Yield, agronomic inputs, and fuel consumption in corn cultivation

| County | Yield (dry) [kg ha$^{-1}$] | N fertilizer [kg N ha$^{-1}$] | P fertilizer [kg $P_2O_5$ ha$^{-1}$] | K fertilizer [kg $K_2O$ ha$^{-1}$] | Herbicides [kg a.i. ha$^{-1}$] | Insecticides [kg a.i. ha$^{-1}$] | Lime [kg ha$^{-1}$] | Diesel [MJ ha$^{-1}$] | Gasoline [MJ ha$^{-1}$] | LPG [MJ ha$^{-1}$] | Electricity [MJ ha$^{-1}$] | Natural gas [MJ ha$^{-1}$] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hardin (IA) | 8,758 | 143 | 67 | 84 | 2.1 | 0.1 | 23 | 1,546 | 362 | 1,582 | 150 | 62 |
| Fulton (IL) | 8,151 | 178 | 93 | 129 | 2.9 | 0.2 | 23 | 1,243 | 453 | 615 | 86 | 187 |
| Tuscola (MI) | 6,258 | 140 | 55 | 114 | 2.5 | 0.1 | 23 | 2,420 | 755 | 791 | 228 | 541 |
| Morrison (MN) | 5,930 | 134 | 56 | 71 | 1.8 | 0.02 | 23 | 1,815 | 513 | 1,867 | 239 | 111 |
| Freeborn (MN) | 8,298 | 134 | 56 | 71 | 1.8 | 0.02 | 23 | 1,815 | 513 | 1,867 | 239 | 111 |
| Macon (MO) | 6,291 | 181 | 68 | 87 | 2.0 | 0.04 | 23 | 1,680 | 755 | 527 | 307 | 164 |
| Hamilton (NE) | 9,053 | 155 | 42 | 21 | 2.0 | 0.1 | 23 | 4,167 | 634 | 901 | 1,361 | 2,339 |
| Codington (SD) | 6,477 | 110 | 53 | 29 | 1.1 | 0.0 | 23 | 1,479 | 453 | 110 | 245 | 17 |

*LPG* liquefied petroleum gas, *a.i.* active ingredient

estimated by a linear approximation expressed in Eqs. 1 and 2, respectively:

$$\text{Carbon sequestration rate}: \Delta S^t = \left(\frac{S^t - S^0}{t}\right), \tag{1}$$

$$\text{Nitrogen} - \text{related emission rate}: N_i^t = \frac{\sum^t \mathrm{NR}_i^t}{t} \tag{2}$$

where $\Delta S^t$ is the annual carbon sequestration rate over a given time $t$ [kg C ha$^{-1}$ year$^{-1}$], $S^t$ is the soil organic carbon level at given time $t$ [kg C ha$^{-1}$], and $S^0$ is the initial soil organic carbon level [kg C ha$^{-1}$]. $N_i^t$ is the nitrogen-related emission rate over a given time [kg ha$^{-1}$ year$^{-1}$] and $NR_i^t$ is the annual nitrogen-related emission at time $t$ [kg ha$^{-1}$]. Subscript $i$ represents the type of nitrogen-related emission (i.e., $N_2O$, $NO_x$, $NO_3^-$). $t$ is the simulation period years.

### 3.1 Allocation

In the CSR system in which corn grain and stover are harvested, the system expansion approach (ISO 14041 1998) is used in order to estimate the environmental burdens of the corn stover alone. The environmental burden associated with corn grain calculated in the CRN system is subtracted from the total burden of both corn grain and corn stover in the CSR system. Figure 2 is a pictorial representation of the system expansion method. The results of the system expansion approach are only the incremental effects of harvesting corn stover. The effects include changes in soil organic carbon level, nitrogen-related emissions (e.g., $N_2O$, $NO_x$, $NO_3^-$), phosphorus loss, additional nutrient requirements in the subsequent growing season, and fuel consumption in harvesting corn stover. A sensitivity analysis on the allocation procedure is included in this study.

### 3.2 Sensitivity analysis

The DAYCENT model spin-up period and crop history, rate of lime application, ammonia loss, and the allocation procedure for corn grain and corn stover are studied as sensitivity analysis. The following aspects are investigated in scenario analyses: (1) collecting only the cob portion of the corn stover in a first pass along with the grain, (2) alternative tillage practices (no-tillage and conventional tillage practices), and (3) planting winter cover crops.

### 3.3 Impact assessment

Environmental impact categories considered in this study are total fossil energy use, climate change, acidification, and eutrophication. Total fossil energy use is evaluated by multiplying the total amount of each fossil fuel used by the

**Table 2** Tillage practices, soil texture, climate information (Conservation Technology Information Center 2003; National Climatic Data Center 2007; NSSC Soil Survey Laboratory 2005), and stover removal rate

| | Tillage practice[a] [%] | | | | Soil texture | | Temperature[b] [°C] | | Precipitation[b] [Cm] | Corn stover removal rate [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| | NT | MT | RT | CNT | Clay | Sand | Max | Min | | |
| Hardin (IA) | 13.9 | 25.2 | 39.9 | 21.1 | 0.3 | 0.2 | 24 | 11 | 10 | 50 |
| Fulton (IL) | 13.1 | 21.9 | 25.4 | 39.5 | 0.2 | 0.2 | 26 | 13 | 10 | 50 |
| Tuscola (MI) | 15.6 | 17.7 | 24.1 | 42.5 | 0.3 | 0.2 | 24 | 10 | 8 | 50 |
| Morrison (MN) | 0.9 | 16.3 | 33.1 | 49.8 | 0.3 | 0.2 | 23 | 11 | 10 | 50 |
| Freeborn (MN) | 6.8 | 6.8 | 33.8 | 52.6 | 0.1 | 0.7 | 23 | 9 | 8 | 50 |
| Macon (MO) | 18.8 | 4.6 | 31.2 | 45.4 | 0.3 | 0.1 | 27 | 14 | 11 | 25 |
| Hamilton (NE) | 45.5 | 3.4 | 23.8 | 27.3 | 0.2 | 0.2 | 26 | 13 | 9 | 50 |
| Codington (SD) | 26.6 | 31.3 | 11.2 | 31.0 | 0.3 | 0.3 | 23 | 10 | 7 | 45 |

*NT* no-tillage, *MT* mulch tillage, *RT* reduced tillage, *CNT* conventional tillage

[a] Average values from 1995 to 1997

[b] Monthly average during the growing season

associated lower heating value. Among other cradle to farm contributions to climate change, the calculation includes carbon sequestration or release due to increasing or decreasing soil organic carbon and $N_2O$ releases from the soil during cultivation. The 100-year time horizon global warming potentials (IPCC 2001) are used for the climate change calculation. Climate change is measured in $CO_2$ equivalents of greenhouse gas emissions and is referred to as greenhouse gas emissions throughout this study. Air acidification is evaluated with the characterization factors suggested by Potting et al. (1998), and eutrophication is estimated by the Institute of Environmental Sciences of Leiden University (CML) characterization factors (Guinée 2002). Soil organic carbon sequestration rate is also considered as an indicator of environmental performance. The initial intention was to use the Environmental Protection Agency's Tools for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) methods for analysis (EPA 2008). However, at the time of this analysis, TRACI II was not yet published.

## 4 Results

### 4.1 Soil organic carbon and nitrogen-related emissions

The DAYCENT model results, shown in Table 3, are given on a per hectare of land per year basis. Simulations from the DAYCENT model predict that the CRN system under the current tillage practices sequesters carbon as soil organic carbon at rates of 43 to 444 kg $CO_2$ eq. $ha^{-1}$ $year^{-1}$, and the CSR system under the current tillage practices sequesters carbon at rates of −144 to 153 kg $CO_2$ eq. $ha^{-1}$ $year^{-1}$. In all cases, removing corn stover lowers SOC accumulation versus removing corn grain only. A negative rate implies that soil organic carbon level decreases. In Morrison, Freeborn, and Macon counties, removing the corn stover would decrease the soil organic carbon level. It is noted that conventional tillage practices dominate in these three counties. Simulations covered later in the paper show that conventional tillage sequesters less carbon than no-tillage operations.

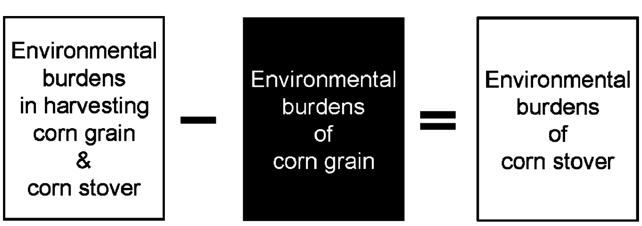


**Fig. 2** System expansion allocation method

The DAYCENT model simulations show that removing corn stover from the fields reduces nitrogen-related emissions (i.e., $N_2O$, $NO_x$, and $NO_3^-$ leaching) because there is less residual biomass available to be converted into nitrogen-related emissions. The results from the DAYCENT model are summarized in Table 3. As seen in Table 3, carbon sequestered and nitrogen-related emissions vary significantly with location. These variations are primarily due to soil properties, climate conditions, and cropping management practices.

### 4.2 Impact assessment

Results from the impact assessment are summarized in Tables 4 and 5. The value for agrochemicals in Tables 4 and 5 includes the environmental impacts associated with fertilizers and agrochemicals. Field operations represent the environmental impacts of fuel consumption during field operations (e.g., plowing, planting, harvesting, etc.). Field emissions indicate the environmental impacts generated from soil, for example, the impacts associated with carbon sequestered and $N_2O$ emissions from soil. Avoided grain is

**Table 3** DAYCENT simulation results for corn cultivation with and without stover collection under the current tillage practices on a per hectare of land per year basis

| | CRN system | | | | CSR system | | | |
|---|---|---|---|---|---|---|---|---|
| | $N_2O$ [kg $N_2O$–N $ha^{-1}$ $year^{-1}$] | $NO_x$ [kg $NO_x$–N $ha^{-1}$ $year^{-1}$] | $NO_3^-$ [kg $NO_3^-$–N $ha^{-1}$ $year^{-1}$] | Carbon sequestered by soil [kg $CO_2$ eq. $ha^{-1}$ $year^{-1}$] | $N_2O$ [kg $N_2O$–N $ha^{-1}$ $year^{-1}$] | $NO_x$ [kg $NO_x$–N $ha^{-1}$ $year^{-1}$] | $NO_3^-$ [kg $NO_3^-$–N $ha^{-1}$ $year^{-1}$] | Carbon sequestered by soil [kg $CO_2$ eq. $ha^{-1}$ $year^{-1}$] |
| Hardin (IA) | 3.1 | 20.0 | 1.4 | 317 | 2.7 | 18.6 | 1.3 | 46 |
| Fulton (IL) | 4.8 | 35.1 | 9.3 | 305 | 4.3 | 32.6 | 6.1 | 46 |
| Tuscola (MI) | 3.4 | 24.5 | 12.6 | 247 | 2.8 | 21.7 | 8.6 | 0.8 |
| Morrison (MN) | 3.5 | 26.1 | 8.4 | 146 | 3.0 | 23.0 | 5.6 | −36 |
| Freeborn (MN) | 5.2 | 10.5 | 1.2 | 82 | 4.6 | 9.7 | 1.0 | −144 |
| Macon (MO) | 8.5 | 31.6 | 19.2 | 43 | 8.0 | 30.1 | 17.3 | −52 |
| Hamilton (NE) | 4.3 | 21.4 | 6.0 | 444 | 3.7 | 19.5 | 3.6 | 153 |
| Codington (SD) | 3.0 | 18.0 | 0.7 | 359 | 2.5 | 17.0 | 0.5 | 141 |

*CRN system* corn produced for grain only, without collecting corn stover, *CSR system* corn produced for corn grain and corn stover harvest

the environmental impacts associated with only the corn grain, which is subtracted from the CSR system. Then, the overall number for corn stover is the environmental burden of harvesting only the corn stover.

The total fossil energy used in corn grain production ranges from 2.1 to 3.3 MJ $kg^{-1}$ of dry corn grain. Over 50% of total fossil energy is associated with agrochemical production in most counties (except Hamilton County in Nebraska due to irrigation). Except for Hamilton County, the primary cause for total fossil energy consumption is nitrogen fertilizer, accounting for over 30% of total fossil energy inputs. Due to the significant contribution of nitrogen fertilizer to the total environmental burden of corn grain and stover production, further sensitivities on this input will be considered. Total fossil energy associated with corn stover production ranges from 0.85 to 0.98 MJ $kg^{-1}$ of dry corn stover. The corn stover production system requires only energy for harvesting corn stover and for additional nutrients in the subsequent growing season. The local variations in corn stover production are relatively small, compared to the variations in corn grain production.

Greenhouse gas emissions associated with corn grain production are 254 to 824 g $CO_2$ eq. $kg^{-1}$ of dry corn grain (see Tables 4 and 5). For each county, field emissions (sum of carbon sequestration and $N_2O$ emissions from soil) are the most significant contributor to total greenhouse gas emissions. The lowest greenhouse gas emissions occur in Hardin County in Iowa in which greenhouse gas emissions from the soil are the lowest among all the counties. Macon County in Missouri produces the highest greenhouse gas emissions in corn grain production because of higher $N_2O$ emissions from soil and lower carbon sequestration. Macon County in Missouri has the highest application rate of nitrogen fertilizer among the counties considered in this study. Greenhouse gas emissions associated with agrochemicals in most counties (except for Hamilton County in Nebraska) are higher than those of field operations.

Greenhouse gas emissions associated with producing corn stover are −39 to 89 $CO_2$ eq. $kg^{-1}$ of dry corn stover (see Tables 4 and 5). Although removing corn stover from the fields could reduce the accumulation rate of soil organic carbon, the overall greenhouse gas emissions associated with corn stover are lower than that of corn grain by over 65%. The reasons for the lower greenhouse gas emissions in corn stover production are: (1) lower $N_2O$ emissions from soil and (2) lower greenhouse gas emissions from agrochemicals and field operations (accounting for only additional nutrients needed in the subsequent growing season due to harvesting corn stover). Corn stover produced in Macon County in Missouri has a greenhouse gas emissions credit due to the lower allowable stover removal rate of 25% (compared to 45% to 50% in all other counties studied). For every 1 kg of corn stover removed in Macon

**Table 4** Results from the impact assessment in the reference case: Total fossil energy

| | Corn grain [MJ kg$^{-1}$] | | | Corn stover [MJ kg$^{-1}$] | | | |
|---|---|---|---|---|---|---|---|
| | Overall | Agrochemicals | Field operations | Overall | Agrochemicals | Field operations | Avoided grain |
| Total fossil energy | | | | | | | |
| Hardin (IA) | 2.1 | 1.6 | 0.5 | 1.0 | 3.9 | 1.4 | −4.3 |
| Fulton (IL) | 2.7 | 2.3 | 0.4 | 0.9 | 5.2 | 1.1 | −5.4 |
| Tuscola (MI) | 3.1 | 2.2 | 0.9 | 0.8 | 4.9 | 2.1 | −6.2 |
| Morrison (MN) | 3.1 | 2.2 | 0.9 | 0.9 | 4.9 | 2.2 | −6.2 |
| Freeborn (MN) | 2.2 | 1.5 | 0.7 | 1.0 | 3.7 | 1.7 | −4.4 |
| Macon (MO) | 3.3 | 2.6 | 0.7 | 1.0 | 11.1 | 3.1 | −13.2 |
| Hamilton (NE) | 3.0 | 1.4 | 1.6 | 0.9 | 3.4 | 3.5 | −6.0 |
| Codington (SD) | 2.2 | 1.7 | 0.5 | 0.9 | 4.3 | 1.4 | −4.8 |

County, 4 kg of corn grain are produced and so the avoided grain credit is for 4 kg of corn grain. Unlike total fossil energy, greenhouse gas emissions associated with corn stover production show larger local variations due to local differences in carbon sequestration, $N_2O$ emissions from the soil, and corn stover removal rate. The local variations of greenhouse gas emissions associated with corn grain are even larger because of local differences in nitrogen fertilizer application, soil properties, and climate conditions.

Acidification associated with the corn grain production system ranges from 2.7 to 7.8 g $SO_x$ eq. kg$^{-1}$ (see Tables 4 and 5). Nitrogen oxide emissions from the soil are the

**Table 5** Results from the impact assessment in the reference case: Greenhouse gas emissions, acidification and eutrophication

| | Corn grain | | | | Corn stover | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Overall | Agrochemicals | Field operations | Field emissions | Overall | Agrochemicals | Field operations | Field emissions | Avoided grain |
| Greenhouse gas emissions [g $CO_2$ eq. kg$^{-1}$] | | | | | | | | | |
| Hardin (IA) | 254 | 90 | 37 | 127 | 90 | 214 | 101 | 282 | −507 |
| Fulton (IL) | 389 | 125 | 27 | 237 | 68 | 284 | 82 | 478 | −776 |
| Tuscola (MI) | 401 | 123 | 68 | 210 | 50 | 281 | 157 | 414 | −802 |
| Morrison (MN) | 442 | 121 | 69 | 252 | 28 | 276 | 158 | 477 | −883 |
| Freeborn (MN) | 416 | 86 | 49 | 281 | 58 | 207 | 126 | 558 | −833 |
| Macon (MO) | 825 | 149 | 51 | 625 | −40 | 630 | 232 | 2395 | −3297 |
| Hamilton (NE) | 370 | 84 | 113 | 173 | 60 | 203 | 252 | 343 | −738 |
| Codington (SD) | 289 | 90 | 38 | 161 | 53 | 234 | 105 | 356 | −642 |
| Acidification [g $SO_2$ eq. kg$^{-1}$] | | | | | | | | | |
| Hardin (IA) | 3.8 | 1.0 | 0.2 | 2.6 | 0.3 | 2.3 | 0.8 | 4.9 | −7.6 |
| Fulton (IL) | 6.5 | 1.3 | 0.2 | 5.0 | 0.0 | 3.0 | 0.7 | 9.2 | −12.9 |
| Tuscola (MI) | 6.4 | 1.3 | 0.6 | 4.5 | −0.5 | 3.0 | 1.3 | 8.0 | −12.7 |
| Morrison (MN) | 6.8 | 1.3 | 0.4 | 5.1 | −0.6 | 3.0 | 1.1 | 8.9 | −13.6 |
| Freeborn (MN) | 2.7 | 0.9 | 0.3 | 1.5 | 0.5 | 2.2 | 0.9 | 2.7 | −5.4 |
| Macon (MO) | 7.8 | 1.6 | 0.4 | 5.8 | −0.4 | 6.8 | 1.9 | 22.0 | −31.2 |
| Hamilton (NE) | 4.3 | 0.9 | 0.7 | 2.7 | 0.2 | 2.2 | 1.7 | 5.0 | −8.7 |
| Codington (SD) | 4.5 | 1.0 | 0.3 | 3.2 | 0.2 | 2.5 | 0.9 | 6.7 | −9.9 |
| Eutrophication [g $PO_4^{3-}$ eq. kg$^{-1}$] | | | | | | | | | |
| Hardin (IA) | 0.9 | 0.1 | 0.04 | 0.8 | −0.1 | 0.3 | 0.1 | 1.3 | −1.9 |
| Fulton (IL) | 1.7 | 0.2 | 0.03 | 1.5 | −0.3 | 0.4 | 0.1 | 2.5 | −3.3 |
| Tuscola (MI) | 1.8 | 0.2 | 0.1 | 1.5 | −0.5 | 0.4 | 0.2 | 2.5 | −3.6 |
| Morrison (MN) | 1.8 | 0.2 | 0.1 | 1.5 | −0.5 | 0.4 | 0.2 | 2.5 | −3.5 |
| Freeborn (MN) | 0.7 | 0.1 | 0.1 | 0.5 | 0.0 | 0.3 | 0.1 | 0.9 | −1.4 |
| Macon (MO) | 2.3 | 0.2 | 0.1 | 2.0 | −0.5 | 1.0 | 0.3 | 7.5 | −9.3 |
| Hamilton (NE) | 1.1 | 0.1 | 0.1 | 0.8 | −0.2 | 0.3 | 0.2 | 1.4 | −2.2 |
| Codington (SD) | 1.0 | 0.1 | 0.1 | 0.9 | −0.1 | 0.4 | 0.1 | 1.7 | −2.3 |

primary acidification source, followed by ammonia from nitrogen fertilizer production. Acidification results for corn stover in some counties are negative because removing corn stover from the fields reduces $NO_x$ emissions from the soil. Eutrophication in corn grain production ranges from 0.7 to 2.3 g $PO_4^{3-}$ eq. $kg^{-1}$ (see Tables 4 and 5). The primary eutrophication sources are nitrogen-related emissions from the soil (i.e., $NO_x$, $NO_3^-$ leaching). This implies that nitrogen fertilizer would have the most significant effect on these two local impacts. For all counties, the eutrophication results for corn stover are negative for the same reasons addressed in acidification. The local variations in acidification and eutrophication are largely due to differing application rates of nitrogen fertilizer, soil properties, and climate conditions.

## 4.3 Sensitivity analyses

*DAYCENT model* Two aspects are considered: (1) the spin-up period (1,860 years) and (2) crop history from 1861 to 1994. Fulton County (IL) is chosen to implement these sensitivity analyses. The extension of the spin-up period to 6,000 years does not significantly change the overall environmental performance of biomass. The alternative crop history also does not affect significantly the overall environmental performance. To study the effect of crop history on DAYCENT model results, a corn–soybean rotation is assumed from 1965 to 1974 instead of continuous corn cultivation. The soil organic carbon sequestration rate changes with the different crop history, but the trend remains the same. Differences in overall greenhouse gas emissions between the different crop histories are less than 5%. Greenhouse gas emissions of corn grain are 386 g $CO_2$ eq. $kg^{-1}$ in the “spin-up period” sensitivity analysis and 374 g $CO_2$ eq. $kg^{-1}$ in the “crop history” sensitivity analysis, while greenhouse gas emissions of corn grain in the reference case are 388 g $CO_2$ eq. $kg^{-1}$.

*Rate of lime application* Lime application rates from Wu et al. (2006b) are much higher than the values used in this study, which are from the study by Shapouri et al. (2002). Using the lime rate from the study by Wu et al. (2006b; 469 kg $ha^{-1}$) in corn production, greenhouse gas emissions of corn are increased by up to 14%, while the total fossil energy used and local impacts (i.e., acidification and eutrophication) are increased by less than 6%. The primary reason for the significant increase in the greenhouse gas emissions of corn production is the $CO_2$ released from the soil due to increased lime application.

*Ammonia loss* Meisinger and Randall (1991) show that ammonia loss from N fertilizer ranges from 0% to 2% when N fertilizer is incorporated and soil pH is below 7. In the sensitivity analysis, we assume that about 2% of N fertilizer is lost via volatilization just after application of the N fertilizer to determine the effects of ammonia loss. Macon County in Missouri is selected in the analysis because the application rate of Macon County is highest among other counties in this study. If ammonia volatilization occurs, ammonia loss could affect other nitrogen losses (e.g., $N_2O$, $NO_x$, $NO_3^-$) and soil organic carbon sequestration rate as well as corn yield. Results show that acidification is the most affected environmental impact out of the impacts included in this study by ammonia volatilization but its difference from value in the reference case is only about 6%. Other impacts are less affected (less than 3%).

*Allocation between corn grain and corn stover* System expansion is the preferred allocation method, as it properly assigns to corn stover only the environmental burdens associated with corn stover harvest, which include changes in soil organic carbon and nitrogen dynamics, additional fuel consumption, and additional nutrient requirements in the subsequent growing season. Consequently, the benefits of removing residual biomass from the field such as reduced $NO_3^-$ leaching are attributed all to corn stover because the benefit can only be achieved with corn stover removal. The ISO LCA standards recommend that allocation should be avoided by subdivision of the system or system expansion, wherever possible (ISO 14041 1998). For example, the GREET tool developed by Michael Wang of the Argonne National Lab also recommends system expansion (Wang 2000).

The ISO LCA standards also suggest that other allocation procedures (e.g., mass basis, etc.) be considered if allocation cannot be avoided. The mass allocation approach allocates the overall environmental burdens to corn stover by its mass fraction. Since the mass of stover equals the mass of grain, the environmental burdens associated with corn stover are equal to those of corn grain produced in the CSR system. This equates to a significant increase in the environmental impact of corn stover with an associated decline in the environmental impact of corn grain, as compared to the system expansion method. Differences in the final results obtained between the system expansion and the mass allocation approaches for corn stover are shown in Fig. 3. The environmental impacts associated with corn stover considered in this study are always higher in the mass allocation approach than in the system expansion approach. This sensitivity analysis indicates that the allocation approach is a critical factor in estimating the environmental burdens of corn stover.

## 4.4 Scenario analyses

*Corn cob* Corn cobs are produced at a rate of approximately 17 wt.% of corn grain yield on a dry basis (Watson

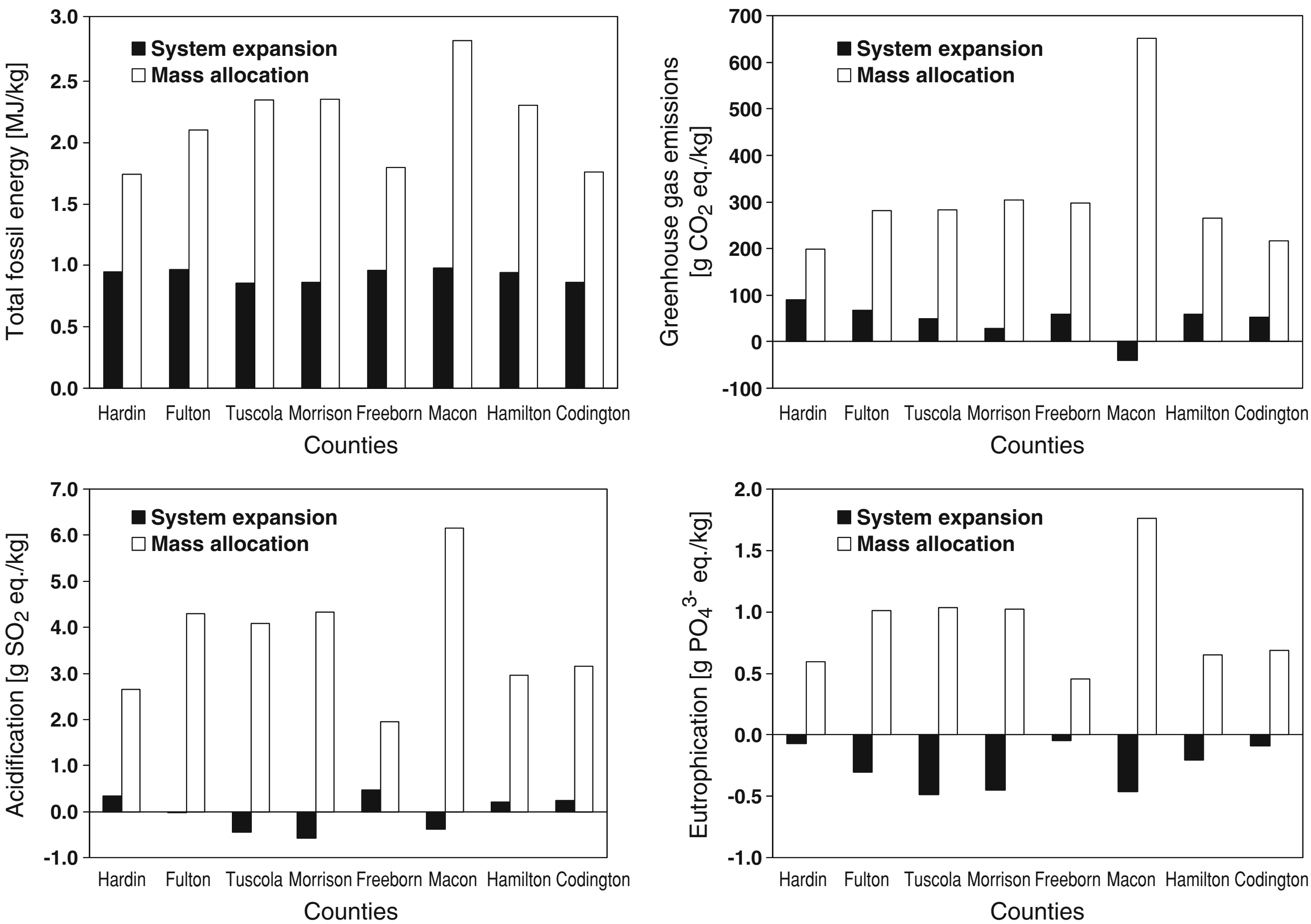


**Fig. 3** Effects of the allocation procedures on the environmental impacts of corn stover [*black bar* system expansion approach, *white bar* mass allocation approach]

and Ramstad 1987). Corn cob harvest is modeled in DAYCENT as a 17% stover removal collection scenario. DAYCENT does not differentiate among various fractions of corn stover. Unlike corn stover, corn cobs enter the combine and could be harvested simultaneously with corn grain, using an additional wagon. This system is referred to as the CCB system. When corn cobs are to be the feedstock in the ICBR process, it is assumed that a dryer would be required to reduce moisture content from 25% to 15%. Drying 1 kg of dry corn cob consumes 2.9 W h of electricity for hauling corn cob and blowing hot air and 0.3 MJ of natural gas for heating the air (Farm Fan Inc. 2007). The DAYCENT model predicts that collecting corn cob decreases the accumulation rate of soil organic carbon and reduces nitrogen-related emissions from soil (i.e., $N_2O$, $NO_x$, $NO_3$) versus just collecting corn grain. Results are presented in Table 6 (see Table 3 for harvesting corn grain or the full allowable amount of stover). The trend in the results, as shown in Fig. 3, for corn stover in the CSR system is the same for the corn cob in the CCB system.

Figure 4 illustrates the comparison between corn stover and corn cobs for the environmental impacts included in the study. In general, there is very little difference between the production of corn stover and corn cobs in terms of total fossil energy use, greenhouse gas emissions, acidification, and eutrophication. In most counties, corn cobs are only slightly better than corn stover for the impacts shown.

*Tillage practice* No-tillage and conventional tillage practices are compared to current tillage practices in Fulton County (IL) to determine their effects on the environmental performance of corn grain and corn stover. The major differences between these two tillage practices are fuel consumption, soil organic carbon, and nitrogen dynamics. It is assumed that the tillage practices do not greatly affect other factors such as corn yield, fertilizer application rates, etc. (Christensen 2002). Fuel consumption associated with the tillage operation can be estimated assuming that only diesel fuel is consumed in the tillage operations (Natural Resources Conservation Service 2007).

The purpose of this scenario analysis is to determine the environmental changes from the current tillage practices. Therefore, corn grain grown under the current tillage practices is chosen as the avoided product for corn grain

**Table 6** Results from the DAYCENT model in the CCB system

| | CCB system | | | |
|---|---|---|---|---|
| | $N_2O$ [kg $N_2O$–N $ha^{-1}$ $year^{-1}$] | $NO_x$ [kg $NO_x$–N $ha^{-1}$ $year^{-1}$] | $NO_3^-$ [kg $NO_3^-$–N $ha^{-1}$ $year^{-1}$] | Carbon sequestered by soil [kg $CO_2$ eq. $ha^{-1}$ $year^{-1}$] |
| Hardin (IA) | 2.9 | 19.4 | 1.4 | 221 |
| Fulton (IL) | 4.6 | 34.0 | 8.2 | 214 |
| Tuscola (MI) | 3.2 | 23.5 | 11.3 | 173 |
| Morrison (MN) | 3.3 | 24.9 | 7.3 | 79 |
| Freeborn (MN) | 5.0 | 10.2 | 1.1 | 2 |
| Macon (MO) | 8.1 | 30.5 | 17.9 | −25 |
| Hamilton (NE) | 4.1 | 20.5 | 4.5 | 343 |
| Codington (SD) | 2.9 | 17.5 | 0.6 | 272 |

*CCB system* corn produced for grain and corn cob harvest

in the CSR system. The environmental burdens associated with corn grain under the current tillage practices are subtracted from the total environmental burden of the CSR system for each alternative tillage practice considered. Changing tillage practices from the current practice to no-tillage reduces overall diesel fuel use by 12% to 44%. Changing from the current practice to conventional tillage increased overall diesel fuel use by 3% to 20%. The DAYCENT model predicts that no-tillage practices increase soil organic carbon level so that even the CSR system could sequester carbon as soil organic carbon in all the counties considered in this study. For no-tillage practices, the DAYCENT model carbon sequestration rate results range from 292 to 559 kg $CO_2$ eq. $ha^{-1}$ $year^{-1}$. Figures 5 and 6

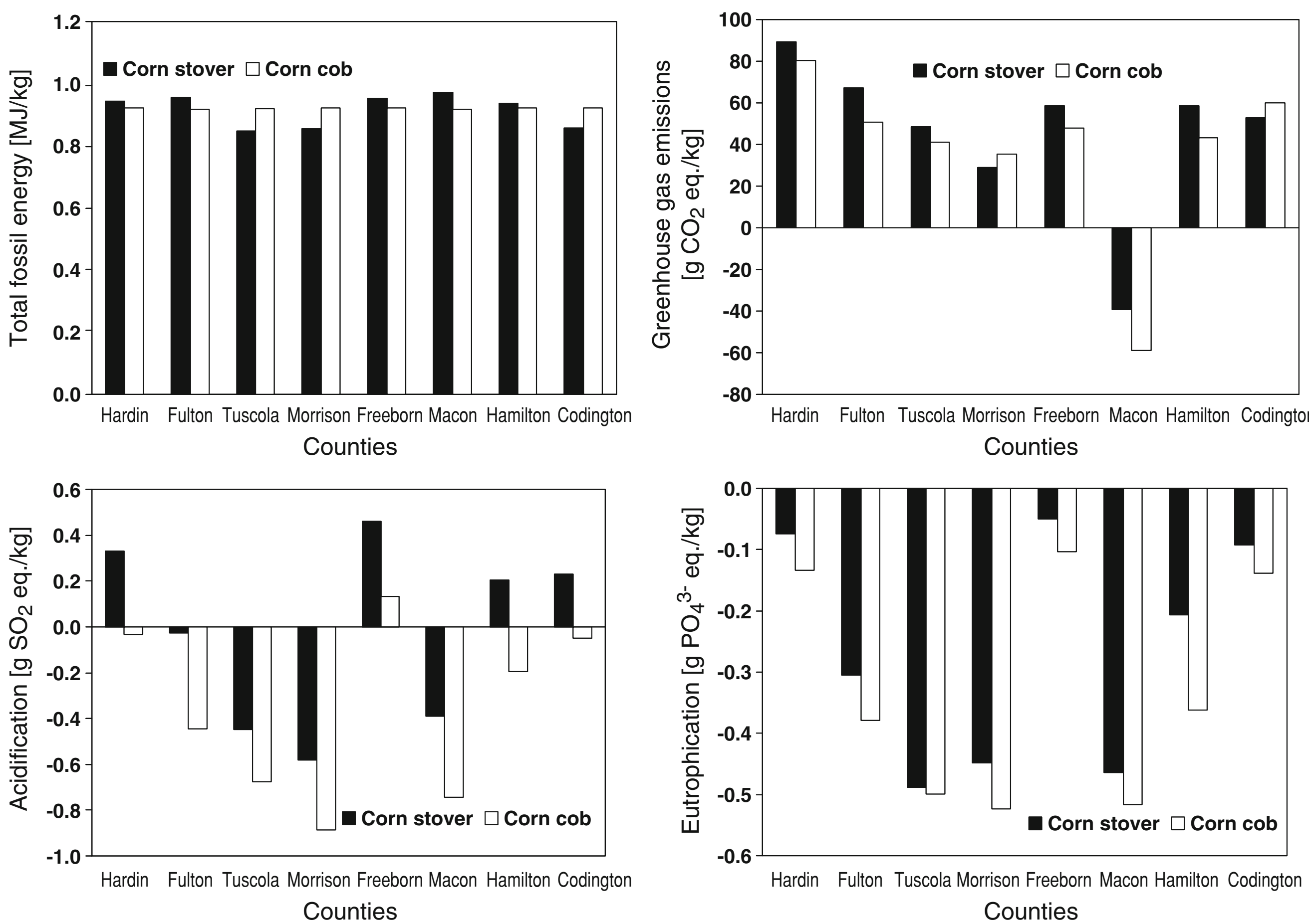


**Fig. 4** Comparison of the environmental impacts between corn cob and stover

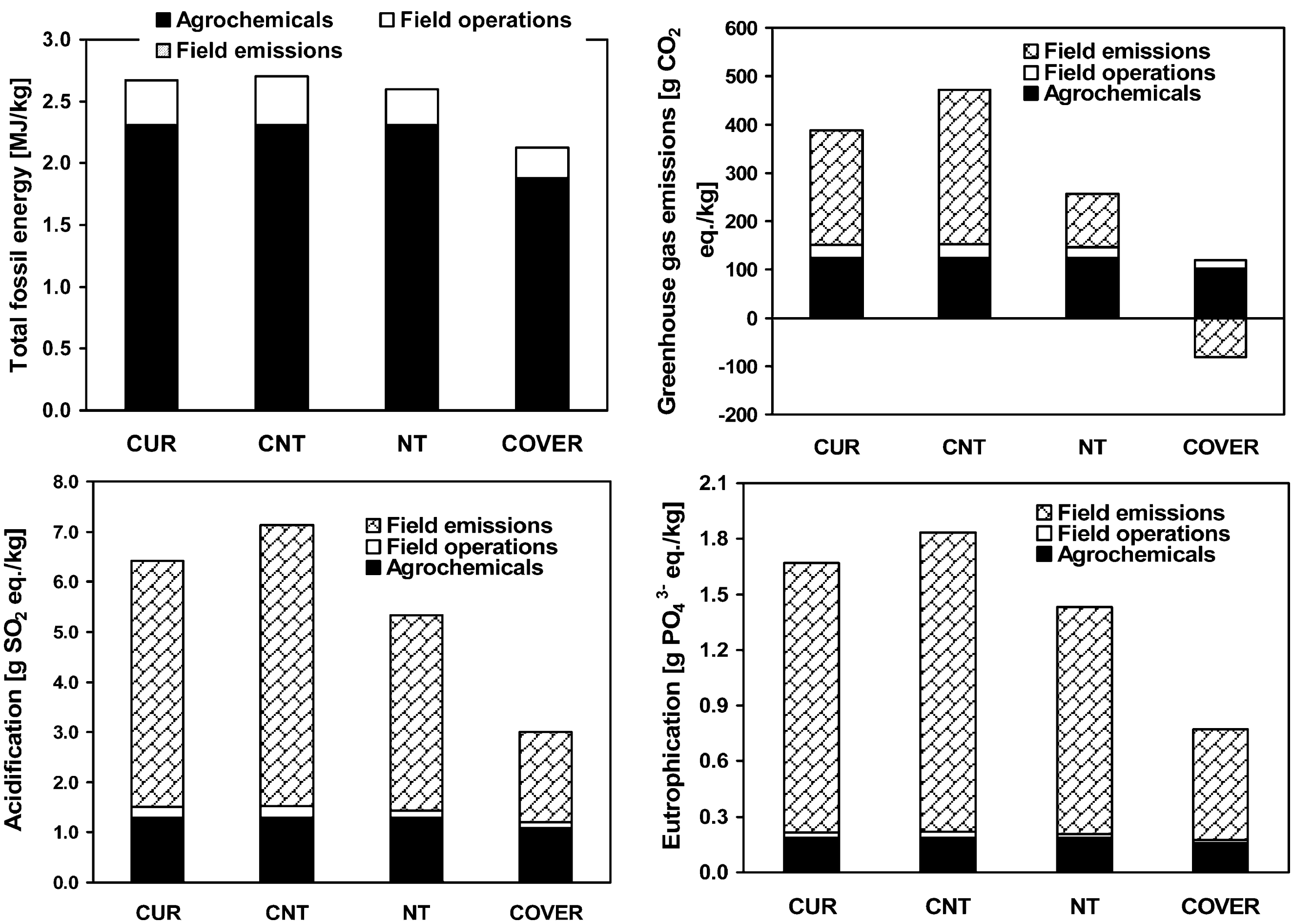


**Fig. 5** Effects of tillage practices and planting winter cover crop on the environmental performance of corn grain in Fulton County (IL) [*NT* no-tillage practice, *CUR* current tillage practice, *CNT* conventional tillage practice, *COVER* winter cover crops planted in no-tilled corn culture]

show that no-tillage practices could reduce total fossil energy, greenhouse gas emissions, acidification, and eutrophication. Converting to no-tillage from the current tillage practices could reduce greenhouse gas emissions associated with field emissions of corn grain and corn stover by about 53% and 45%, respectively, because of more carbon sequestered and less nitrous oxide emissions from the soil. Even though this study does not differentiate herbicide (pesticide) rates between no-tillage and conventional tillage practices, a United States Department of Agriculture study (Christensen 2002) shows that no-tillage practice uses slightly less pesticides and slightly more herbicides than the conventional tillage practice. Therefore, more studies on ecotoxicity caused by herbicides or pesticides are needed in a decision-making process.

*Winter cover crops* Winter cover crops are usually planted after harvesting the cash crop and can be killed by herbicides prior to planting the cash crop for the subsequent growing season to protect and improve soil quality (Snapp et al. 2005). Winter cover crops can increase soil organic carbon level and also serve as a nitrogen scavenger (Kuo et al. 1997; Reicosky and Forcella 1998). Winter wheat was selected as the winter cover crop for this analysis. Planting a winter cover crop consumes about 151.6 MJ of diesel per hectare (Lazarus 2000). About 1.1 kg $ha^{-1}$ of herbicides are used to kill winter cover crops before planting corn (Kaspar et al. 2006; Miguez and Bollero 2006; Saini et al. 2006), and applying herbicides requires 36.9 MJ $ha^{-1}$ of diesel per hectare (Saini et al. 2006). No-tillage cultivation in Fulton County (IL) was selected to estimate the effects of winter cover crop use.

The DAYCENT model predicts that planting winter cover crops would increase soil organic carbon levels and reduce nitrogen-related emissions from soil (i.e., $N_2O$, $NO_x$, $NO_3^-$) compared to the standard cropping systems. Returning the winter cover crop to the soil increases the soil organic carbon sequestration rate. Nitrogen losses from soil are reduced because the winter cover crop absorbs nitrogen from the soil during the off growing season. DAYCENT

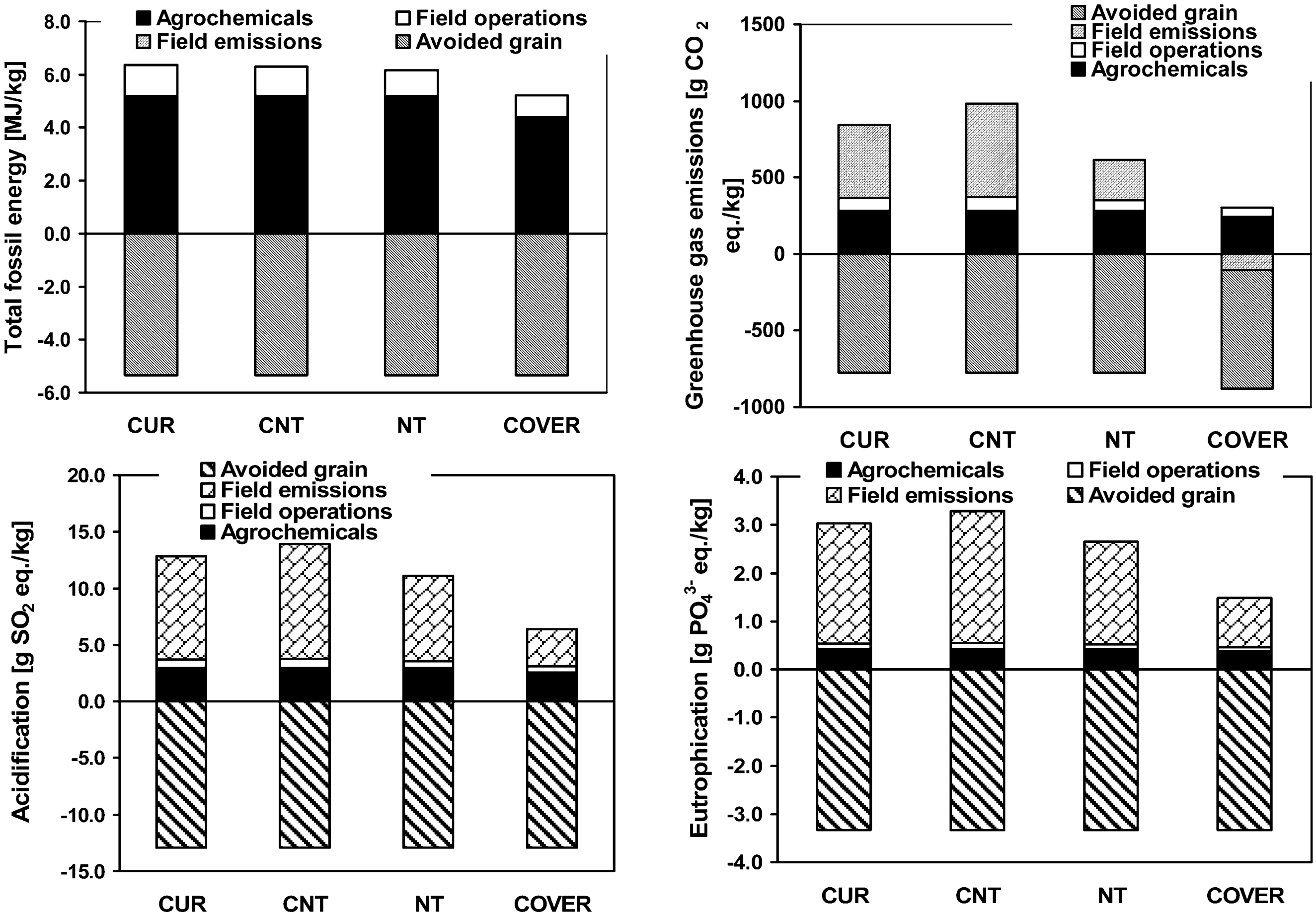


**Fig. 6** Effects of tillage practices and planting winter cover crop on the environmental performance of corn stover in Fulton County (IL) [*NT* no-tillage practice, *CUR* current tillage practice, *CNT* conventional tillage practice, *COVER* winter cover crops planted in no-tilled corn culture]

also predicts that winter cover crops could potentially increase corn grain yields by about 27% in Fulton County because additional nutrients from the winter cover crops are added in the subsequent growing season. The yield increase due to incorporating a winter cover crop practice in the subsequent growing season is taken into account as a benefit. The simulation results with DAYCENT for winter cover crops are consistent with results from other studies (Andraski and Bundy 2005; Kuo et al. 1997; Reicosky and Forcella 1998; Snapp et al. 2005). Even though additional fuel and herbicides are consumed, planting winter cover crops reduces all the environmental impacts considered in this study. The results are illustrated in Figs. 5 and 6. The primary reason for lower total fossil energy is that planting a winter cover crop increases corn yield without additional fertilizer. When a winter cover crop is planted, there is a credit for greenhouse gas emissions associated with field emissions in both corn grain and stover productions (see Figs. 5 and 6). Planting a winter cover crop could significantly reduce acidification and eutrophication associated with field emissions because of lower nitrogen emissions from the soil and higher carbon sequestration rates. However, additional herbicide application to the soil is a concern in planting winter cover crops. Winter cover crops may also be plowed or harvested. More research is recommended to determine effects of different methods to remove winter cover crops.

## 5 Conclusions, recommendations, and perspectives

A LCA has been conducted on corn grain and corn stover production in eight locations in the US Corn Belt. Results show that the environmental performance of corn grain and corn stover varies with the farming location due to crop management, soil properties, and climate conditions. Several general trends were identified from this study. Harvesting corn stover reduces nitrogen-related emissions from soil (i.e., $N_2O$, $NO_x$, $NO_3^-$). The accumulation rate of soil organic carbon is reduced when corn stover is removed, and in some cases, the soil organic carbon level decreases. Corn stover has a lower impact than corn grain in terms of

total fossil energy, greenhouse gas emissions, acidification, and eutrophication.

A decrease in soil organic carbon level is considered unacceptable by the authors. There are farming practice options available which could offset the effect that corn stover removal has on soil organic carbon sequestration rate. Planting winter cover crops or changing from conventional tillage to no-tillage farming could potentially increase the soil organic carbon sequestration rate. Winter cover crops and no-tillage have a positive effect on all LCA impacts included in this study. Removing only the corn cob portion of the stover would reduce the negative impact of stover removal on soil organic carbon sequestration rate while still bringing the benefit of reduced nitrogen-related emissions from the soil.

The nitrogen fertilizer application rate significantly affects the environmental performance of producing corn grain and corn stover. Over 30% of the total fossil energy associated with corn grain and corn stover comes from nitrogen fertilizer. $N_2O$ emitted from the soil is the dominant greenhouse gas, which is associated with nitrogen fertilizer. Nitrogen losses from soil ($NO_x$ and $NO_3^-$), also associated with nitrogen fertilizer, are the primary acidification and eutrophication sources. Planting winter cover crops and transitioning to a no-tillage farming practice are ways to reduce these nitrogen losses from the soil.

Since nitrogen fertilizer use has such a large affect on the corn-farming LCA results, it is important to have the most accurate input data on fertilizer use as possible. If county-level data were to become available, the state-level data used in this study should be validated. In general, county-level modeling is more accurate in estimating the local environmental burdens associated with biomass production than national- or regional-level modeling. When possible, site-specific experimental information on yield, erosion, soil carbon, and nitrogen dynamics should be obtained to reflect the system more accurately. The gathering of site-specific agronomic data is a general difficulty in modeling any bio-based process and further research in this area and field-scale testing is recommended.

The environmental performance of corn stover is affected significantly by the allocation approach chosen. System expansion is the preferred allocation method. In the system expansion approach, incremental fuel usage, additional nutrients in the subsequent growing season, and changes in soil carbon and nitrogen dynamics due to removing corn stover are assigned to only the collected corn stover.

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